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Bell's Theorem on a False Premise: Entropy-Aware Measurement, Forbidden Entropy States, Layer Separation, and a Local Ceiling at $2\sqrt{2}$

Jonathan K. Atoyo, Ike Ogiamien

Prometheus Engineering Research Group, Walnut Creek, California, USA
Email: Jonathanatoyo.prometheus@gmail.com

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Abstract

Bell's theorem derives nonclassical constraints on correlations by assuming that outcomes are functions of local settings and hidden variables, while detectors are ideal, passive readouts. We argue this is a false premise. Real detectors are thermodynamic subsystems in which at least five physically distinct events occur between source and coincidence: the crystal inscribes the constraint into configuration space, the polariser reads it non-destructively ($\Delta S > 0$, photon survives), the photodiode absorbs the photon ($\Delta S \gg 0$, Layer 1 collapse), the coincidence circuit matches timestamps to open the pair layer, and Alice's and Bob's measurements occur independently at spacelike separation. This structure reveals a deeper distinction. Layer 1 is intra-particle coherence—thermodynamically vulnerable in massive particles, producing measurable heat flow and entropy increase at the detector. Layer 2 is the correlation between entangled particles—inscribed at the source, non-thermal, persisting in configuration space with no three-dimensional spatial address. Standard quantum mechanics conflates these under the single word "collapse". We formalise the detector's thermodynamic role with an interactability ratio Ξ that triggers measurement activation when $\Xi > \Xi_c$, a modified path integral where forbidden histories subtract from allowed ones, and an entropy-aware contraction in each correlation channel. The result is a strictly local ceiling $S_{\max} = 2\sqrt{2} L_A L_B \le 2\sqrt{2}$ for the CHSH parameter, where $L_{A,B} \in (0,1]$ encode detector coupling losses. We derive this ceiling in full, rederive Malus' law as an entropy balance, prove no-signalling structurally and thermodynamically, present the exhaustive nine-case analysis of all measurement configurations for entangled pairs, and dissolve the measurement problem by showing that "collapse" is a conflation of two physically distinct events—neither of which is mysterious, observer-dependent, or requires a special postulate. Bell's violation detects that the correlation structure lives in configuration space, not in three-dimensional space. There is no action at a distance because there is no action (Layer 1 is local) and there is no distance (Layer 2 has no three-dimensional address). Einstein is vindicated.

Keywords

Bell's Theorem, CHSH Inequality, Entanglement, Measurement Problem, Configuration Space, No-Signalling, Layer Separation, Tsirelson's Bound, Thermodynamic Measurement, Entropy

1. Introduction

Bell's 1964 theorem [1] and the CHSH formulation [2] are often read as ruling out any local realist account of entanglement. Experiments over five decades—from Aspect's time-varying analysers [3] to loophole-free tests [4]-[6] and cosmic setting choices [7]—indeed violate the classical bound $S \le 2$ while remaining below Tsirelson's $2\sqrt{2}$ [8].

The hidden premise is that measurement is a passive projection with ideal detectors. We replace this with a thermodynamic ontology in which detectors are not black boxes but thermodynamic channels that sort micro-histories into allowed and forbidden sets by entropy accounting.

This replacement has four consequences:

1) **The measurement chain.** Between source and coincidence, at least five physically distinct events occur: crystal inscription (the constraint is written), polariser read (non-destructive, $\Delta S > 0$, photon survives), photon count (destructive, $\Delta S \gg 0$, Layer 1 collapse), coincidence matching (both keys supplied, Layer 2 opened), and Alice's and Bob's independent measurements at spacelike separation. Standard quantum mechanics collapses all five into a single word.

2) **Layer separation.** Layer 1 is intra-particle coherence: local, thermodynamically vulnerable in massive particles (ions, superconducting qubits), and producing measurable thermal traces (heat flow, spectral shifts, entropy increase). Photons are a special case—Layer 1 has no thermal attack surface in free propagation, and the precise mechanism requires further study. Layer 2 is the correlation between entangled particles, inscribed at the source, non-thermal, and persisting in configuration space. The layer separation is confirmed by every Bell test [4]-[6] [9] and every quantum eraser experiment [10]-[12].

3) **No-signalling.** No-signalling is proven from two independent premises: tensor contraction rules (structural) and thermodynamic propagation limits (physical).

4) **Dissolution of the measurement problem.** The measurement problem [13] is a category error produced by conflating Layer 1 inscription (local, thermal, ir-

reversible) with Layer 2 key burial (non-thermal, non-propagating, perfectly recoverable) into a single word.

The entropy-aware CHSH ceiling $S \le 2\sqrt{2}L_A L_B$ is derived in full. The four consequences above provide the physical framework that explains why the result holds.

2. Thermodynamic Ontology of Measurement

2.1. Interactability and Activation: The Layer 1 Threshold

Let Ξ quantify the competition between external entropy inflow and local stabiliser power:

$$\Xi \equiv \frac{T_{\mathrm{loc}} \dot{S}_{\mathrm{ext}}}{P_{\mathrm{stab}}}, \text{ activation when } \Xi > \Xi_c. \tag{1}$$

This threshold governs Layer 1 only. When $\Xi > \Xi_c$, the system can no longer sustain coherent superposition: an inscription event occurs ($\Delta S > 0$), the outcome is permanently selected, and the photon is absorbed or the spin is projected. This is Layer 1 collapse—local, thermal, irreversible.

Layer 2—the correlation between entangled particles—is never subject to this threshold in the Layer 1 sense. Layer 2 can be inscribed in configuration space and transformed by subsequent interactions, but it does not collapse permanently in three-dimensional space (Section 2.4). This distinction is the structural core of the paper.

A detection event is a local thermodynamic transition that crosses the Ξ_c threshold and emits a bounded beacon δJ_B (energy/entropy footprint), with $\delta J_B \le E_{\mathrm{event}}$ by energy audit.

2.2. Physical Scale of the Layer 1 Threshold Ξ_c

The critical threshold Ξ_c determines when Layer 1 inscription becomes unavoidable—when the environment's entropy inflow exceeds the system's capacity to maintain coherent superposition, forcing $\Delta S > 0$.

For a superconducting transmon qubit with interlevel frequency $\omega/2\pi \approx 5\ \mathrm{GHz}$ at $T = 15\ \mathrm{mK}$, the mean thermal photon number is

$$n_{\mathrm{th}}(T) = \left(\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1\right)^{-1} \approx 10^{-7}. \tag{2}$$

The thermal excitation is negligible. $\Xi < \Xi_c$: coherence is maintained. At $T \approx 100\ \mathrm{mK}$, n_{th} rises to ~0.1 and T_1 coherence times drop measurably. At $T > 1\ \mathrm{K}$, $n_{\mathrm{th}} > 1$ and coherent superposition cannot be sustained: $\Xi > \Xi_c$. The threshold corresponds to the temperature at which the thermal photon population overwhelms the qubit's energy gap [14].

For photonic systems, the situation is structurally different. A photon in free propagation has no internal vibrational degrees of freedom and no rest frame in which thermal equilibration could occur [15]. The photon's Ξ remains below

Ξ_c until it physically interacts with a detector (absorption, $\Delta S > 0$). This is the structural reason photonic Bell tests approach $L_A L_B \to 1$: the photon carries no entropy load between source and detector.

Empirically, Ξ_c is calibrated from the T_1 and T_2 coherence times of the specific platform. For SNSPDs at $T \sim 0.6$ - 2 K detecting single photons, the detector activation threshold corresponds to the single-photon energy exceeding the superconducting gap energy of the nanowire—a well-characterised transition.

2.3. The Measurement Chain: At Least Five Distinct Events

The standard treatment models "measurement" as a single operation. Bell's theorem treats it as a function $A(a, \lambda)$. In physical Bell experiments, at least five distinct events occur between source and coincidence, each with different physical character [16]:

(i) Crystal inscription. The source writes both layers simultaneously through spontaneous parametric down-conversion (SPDC). In a Type-I sandwich configuration, two crystals with perpendicular lattice axes are stacked; a 45°-polarised pump photon activates both equally, producing daughter pairs carrying both HH and VV configurations. The constraint written: *same*. In a Type-II crystal, birefringent cone crossing produces daughters with perpendicular polarisations at the ring where both arrangements are structurally present. The constraint written: *opposite*. In both cases, entanglement is a structural property of the source geometry—the crystal writes the constraint into configuration space at the moment of pair creation. Layer 1: each daughter is born with its own coherence in the fourth spatial degree, carrying a three-dimensional address. Layer 2: the relational constraint is inscribed with no three-dimensional address. $\Delta S > 0$.

(ii) Polariser read. At each station, a polarising beam splitter sends the photon down one of two paths depending on its polarisation relative to the transmission axis. $\Delta S > 0$—but the photon is *not destroyed*. The polariser reads the constraint non-destructively by selecting which axis of configuration space is probed—it is the *dimensional selector* [16]. The incidence angle (three-dimensional trajectory) is irrelevant; only the transmission axis matters, because polarisation is a configuration-space property. The photon survives. This is why quantum erasure works: the polariser inscribes without destroying, so a subsequent polariser can re-inscribe.

(iii) Photon count (screen absorption). The photodiode absorbs the photon $\Delta S \gg 0$. The photon is destroyed. This *completes* Layer 1: the particle's coherence, which has existed since the crystal, is permanently closed. Irreversible, thermal, the transition from quantum to classical. Path 1 click: $\uparrow$. Path 2 click: $\downarrow$. The photodiode does not measure—it counts. The measurement already happened at the polariser.

(iv) Coincidence matching. Each station's list alone is featureless: 50% $\uparrow$, 50% $\downarrow$. No pattern. No information about the constraint. The coincidence circuit compares timestamps, tagging clicks from the same pair. The matched list reveals the constraint. This is Layer 2 access: both keys supplied. The circuit does not filter noise from signal—it opens the pair layer [17].

(v) Alice's and Bob's measurements. Each station performs (ii) - (iii) independently at spacelike separation. The correlation between their outcomes lives in Layer 2 and is accessible only through (iv), which requires classical communication.

Bell's theorem collapses all five into a single function $A(a,\lambda)$. The distinctions have physical consequences: the non-destructive polariser read makes quantum erasure possible, the destructive photon count makes Layer 1 collapse irreversible, the crystal inscription makes the correlation exist, and the coincidence circuit makes it readable. The crystal writes. The polariser reads. The photodiode counts. The coincidence circuit opens.

2.4. Layer 1 and Layer 2

The measurement chain (Section 2.3) reveals a structural distinction that extends beyond the apparatus to the correlation itself.

Layer 1 is intra-particle coherence: the internal quantum state of a single particle. Layer 1 is inscribed at the crystal simultaneously with Layer 2—each daughter photon is born with its own coherence structure in the fourth spatial degree. Layer 1 lives in the fourth spatial degree *and* has a three-dimensional address, because it is the actual particle: located somewhere in three-dimensional space, carrying its configuration-space structure as it travels. Layer 1 and Layer 2 are the same in kind—both are coherence, both live in the fourth spatial degree. The difference is the three-dimensional address: Layer 1 has one (it is the particle), Layer 2 does not (it is the relation between particles). This is the structural reason Layer 1 can be fully read by a single detector: the particle is physically co-located with the detector, so one detector has full access to the particle's coherence. One key. Full read. Layer 2 requires both detectors because the relation has no three-dimensional address—it is not located at either detector. Both keys must be presented through coincidence matching. The rank of the inscription tensor equals the number of keys: rank 1 (Layer 1) requires one contraction, rank 2 (Layer 2) requires two [18].

For massive particles (ions, electrons, superconducting qubits), Layer 1 is thermally vulnerable—the particle's internal degrees of freedom couple to the thermal environment through vibrational modes, phonon coupling, and thermal photon absorption. This is what T_1 (energy relaxation) and T_2 (dephasing) coherence times measure. This is what millikelvin cryogenic temperatures protect. Layer 1 inscription is *completed* at the photodiode—the irreversible event where $\Delta S \gg 0$, the photon is absorbed, and the outcome is permanently selected. This completion is the transition from quantum to classical. Layer 1 produces measurable physical traces: heat flow from the measurement apparatus [19], spectral shifts [14], and entropy increase satisfying the Landauer bound [20] [21].

Layer 1 has two distinct failure modes:

Polariser inscription. A polariser physically interacts with the photon's configuration-space structure. $\Delta S > 0$, but the photon survives. This adds a key—for example, a which-path tag at a double slit writes path identity into the polarisation degree of freedom, raising the rank from 1 to 2 [18]. Fringes disappear because an extra key has been added, not because information was destroyed. This mode is recoverable: a subsequent polariser can re-inscribe, conditionally re-merging keys (the quantum eraser mechanism [16]).

Thermal collapse. The photodiode absorbs the photon $\Delta S \gg 0$. The photon is destroyed. Layer 1 is permanently completed. This is what standard quantum mechanics calls "collapse"—irreversible, thermal, final. This mode is not recoverable: the particle no longer exists.

Both are Layer 1 events (the particle's coherence, three-dimensional address). The distinction: polariser inscription is non-destructive and recoverable; thermal collapse is destructive and permanent. Standard quantum mechanics uses one word for both.

Photons are a special case. A photon in free propagation has no rest frame, no internal vibrational degrees of freedom, and no mechanism for thermal relaxation. Layer 1 has no thermal attack surface—the photon either propagates coherently or is absorbed. This is why photonic quantum systems require no cryogenics. The precise mechanism by which photonic Layer 1 differs from massive-particle Layer 1 requires further study; what is established is that photonic coherence is not degraded by the thermal environment between source and detector [15].

Layer 2 is the correlation between entangled particles. It is inscribed at the source—the crystal or parametric process that produced the entangled pair—at the moment of pair creation. The source writes a deterministic constraint: *same* polarisation (Type-I SPDC) or *opposite* polarisation (Type-II SPDC). This constraint persists in configuration space with no three-dimensional spatial address.

Layer 2 is non-thermal. Thermal effects—temperature-driven noise, phonon coupling, thermal photon absorption—do nothing to Layer 2 directly. No heat flows at the distant party when one particle is detected locally. No spectral shift, no entropy change, no physical trace appears at the distant party. This has been confirmed across every loophole-free Bell test [4]-[6] and every quantum eraser experiment [10]-[12]. Cryogenics does not protect Layer 2, because thermal noise does not attack it.

But Layer 2 *is* inscribed by entropy—by physical interactions ($\Delta S > 0$) that affect the system's plane in configuration space. A polariser physically interacts with the photon's polarisation degree of freedom: it inscribes, writing path identity or axis selection into the configuration space structure. This is entropic inscription, not thermal attack. Each such inscription adds a key to the Layer 2 entry and transforms the structure. A subsequent polariser can re-inscribe—conditionally re-merging keys for a subset, which is the mechanism of the quantum eraser [16]. Environmental coupling buries old Layer 2 correlations and writes new ones [16]. Layer 2 never terminates. It transforms. Recovery through post-selection is perfect—the proof that the correlation was never destroyed.

The distinction is precise. Thermal noise attacks Layer 1 (destabilising coherence in massive particles, driving uncontrolled collapse). Uncontrolled Layer 1 collapse indirectly buries Layer 2 keys—this is how thermal decoherence affects entanglement. But thermal noise never touches Layer 2 directly. Cryogenics protects Layer 1; protected Layer 1 preserves Layer 2 access. Entropic inscription (a polariser, a physical interaction with the configuration space plane) can inscribe Layer 2 directly—transforming the structure, adding keys—but this is not thermal.

The standard account conflates these two physically distinct events under the single word "collapse." The present paper's thermodynamic ontology makes the separation explicit: the allowed/forbidden entropy accounting governs Layer 1. The contraction factors $L_{A,B}$ quantify Layer 1 coupling losses. Layer 2 is the correlation structure that the detector accesses through the dimensional key (the polariser angle) but does not permanently destroy—each inscription transforms the Layer 2 structure in configuration space, adding keys, never terminating it.

2.5. Physical Motivation for Forbidden History Subtraction

For a microstate μ in a coarse-grained history γ, define indicator functions

$$\chi_A(\mu) = \begin{cases} 1, & \Xi(\mu) \le \Xi_c, \\ 0, & \text{otherwise}, \end{cases} \quad \chi_F(\mu) = 1 - \chi_A(\mu). \tag{3}$$

The subtraction $\tilde{A} = A - F$ (Equation (6)) is not a mathematical convention. It encodes a physical constraint: forbidden entropy states (FES) are thermodynamically vetoed—they represent configurations that would violate the second law locally [22]. A microstate μ with $\Xi(\mu) > \Xi_c$ has entropy inflow exceeding the system's stabiliser capacity. The system cannot sustain that configuration; it must transition. The transition is the inscription event.

The subtraction implements this veto at the amplitude level. Forbidden histories do not simply vanish—they interfere destructively with allowed histories. This is the physical mechanism behind Malus' law (Equation (8)): the forbidden channel ($\sin^2\theta$) represents amplitude directed into configurations that the polariser's lattice structure cannot sustain as transmitted modes. The energy is dissipated as heat/phonons—a thermodynamic event with $\Delta S > 0$.

The physical consequence is testable: removing the polariser (e.g., switching to time-bin encoding) removes the entropy-sorting step. The framework predicts that L increases toward 1 because the forbidden channel has been eliminated (Section 11).

2.6. Modified Path Integral (History Ledger)

Let $w(\mu)$ be a coarse weight, $\mathcal{S}(\mu)$ the entropy increment, and $\varphi(\mu)$ a phase. Define

$$A[\gamma] = \sum_{\mu\in\gamma} \sqrt{w(\mu)}\, \mathrm{e}^{-\frac{\eta}{2}\mathcal{S}(\mu)} \mathrm{e}^{i\varphi(\mu)} \chi_A(\mu), \tag{4}$$

$$F[\gamma]=\sum_{\mu\in\gamma}\sqrt{w(\mu)}\,\mathrm{e}^{-\frac{\eta}{2}\mathcal{S}(\mu)}\mathrm{e}^{i\varphi(\mu)}\chi_F(\mu), \tag{5}$$

$$\tilde{A}[\gamma]=A[\gamma]-F[\gamma]. \tag{6}$$

The field at a detector point x is then

$$\Psi(x)=\sum_{\gamma}\tilde{A}[\gamma]\mathcal{F}_{\gamma}(x),\quad P(x)=|\Psi(x)|^2, \tag{7}$$

which reduces to standard path summation when $F\to 0$. In the further limit $\eta\to 0$ (no entropy damping), the amplitude reduces to the standard Feynman path integral; as $\eta\to\infty$, high-cost paths are exponentially suppressed and classical mechanics is recovered [22].

2.7. Polarisation as Entropy Sorting: Malus from Balance

Consider a photon incident on a polariser with transmission axis $\hat{t}$; write the incoming state in the analyser basis $\{\hat{t},\hat{t}_\perp\}$ at relative angle θ to the preparation axis. The allowed channel corresponds to coupling into lattice modes aligned with $\hat{t}$; the forbidden channel corresponds to orthogonal coupling dissipated as heat/phonons. The fractions follow projection geometry:

$$p_{\text{allow}}(\theta)=\cos^2\theta,\quad p_{\text{forbid}}(\theta)=\sin^2\theta. \tag{8}$$

Thus, Malus' law is read as an *entropy ledger*: the detector's microphysics spends a fraction $\sin^2\theta$ of amplitude into the entropy sink, leaving $\cos^2\theta$ to be observed.

In the two-component picture, the polariser performs the entropy sorting: it directs the photon into the allowed channel ($\cos^2\theta$) or the forbidden channel ($\sin^2\theta$). The photodiode then inscribes whichever channel the photon entered. The entropy sorting is a Layer 1 precursor—it determines the question. The inscription at the photodiode is Layer 1 completion—it records the answer.

For an entangled pair, the correlation was inscribed at the source. The polariser at each station selects which axis of configuration space is probed—the *dimensional key* [16]. At $\Delta\theta=0^\circ$, both polarisers probe the same axis: the constraint is read as written, deterministic. At $\Delta\theta\neq 0^\circ$, the polarisers probe different axes: $\cos^2(\Delta\theta)$ is the geometric projection between the two probes—the degree to which they address corresponding structure in configuration space. At $\Delta\theta=45^\circ$, the projection equals its complement: the output is indistinguishable from uncorrelated particles. At $\Delta\theta=90^\circ$, the correlation inverts.

2.8. Visibility-Entropy Relation and Phase Survival

Let $\Delta\mathcal{S}$ be the entropy increment borne by the cross-term during measurement. A minimal phenomenology is

$$V(\theta)=V_0\mathrm{e}^{-\eta\Delta\mathcal{S}(\theta)}, \tag{9}$$

which captures reduced visibility under increased mismatch and/or bath asymmetry. In the ideal limit (low-loss optics, SNSPDs):

$$E(\theta) = -\cos 2\theta. \tag{10}$$

3. The Correlation: Inscribed at the Source

3.1. The Inscription Tensor

The inscription tensor κ of rank r [18] stores the correlation structure of any physical system:

$$r = 1:\ \kappa_i = \kappa_0 \hat{n}_i \quad \text{(self-coherent: vector)}, \tag{11}$$

$$r = 2:\ \kappa_{ij} = \kappa_0 \delta_{ij} \quad \text{(entangled pair: “same”)}, \tag{12}$$

$$r = 2:\ \kappa_{ij} = \kappa_0 \varepsilon_{ij} \quad \text{(entangled pair: “opposite”)}. \tag{13}$$

The operation on the tensor is contraction with detector axes:

$$C_r = \kappa_{i_1 \cdots i_r} \hat{a}_1^{i_1} \cdots \hat{a}_r^{i_r}. \tag{14}$$

The Born rule gives the probability: $P = |C_r|^2 / \sum_{\text{outcomes}} |C_r|^2$.

3.2. Same and Opposite: The Only Two Constraints

In two-dimensional configuration space, δ_{ij} and ε_{ij} are the only two isotropic rank-2 tensors. The geometry permits exactly two qualitative constraints between two parties—same and opposite—and nothing else. This is not a contingent fact about particular quantum states. It is the complete set of isotropic relational structures available.

For the “same” constraint ($\kappa_{ij} = \kappa_0\, \delta_{ij}$), the joint probabilities are:

$$\begin{aligned} &P(\uparrow\uparrow) = \frac{1}{2}\cos^2(\Delta\theta),\ P(\uparrow\downarrow) = \frac{1}{2}\sin^2(\Delta\theta), \\ &P(\downarrow\uparrow) = \frac{1}{2}\sin^2(\Delta\theta),\ P(\downarrow\downarrow) = \frac{1}{2}\cos^2(\Delta\theta). \end{aligned} \tag{15}$$

For the “opposite” constraint ($\kappa_{ij} = \kappa_0\, \varepsilon_{ij}$), swap $\cos^2 \leftrightarrow \sin^2$. In both cases, each party’s marginal sums to $\frac{1}{2}$. No-signalling is structural.

4. What Both Stations See Alone

Alice, measuring alone at any angle, sees: 50% $\uparrow$, 50% $\downarrow$. Always. Regardless of what Bob does, when he does it, or whether he does anything at all. Bob sees the same.

This is proven by partial contraction of the rank-2 inscription tensor [17]:

$$P_B(+) = \frac{1}{2}\cos^2(\theta_B - \theta_A) + \frac{1}{2}\sin^2(\theta_B - \theta_A) = \frac{1}{2}, \tag{16}$$

forced by the trigonometric identity $\cos^2\alpha + \sin^2\alpha = 1$. The marginal is independent of θ_A. This result was *computed*, not assumed. No step contains no-signalling as a premise.

The 50/50 is not noise. It is degeneracy. The constraint says "same" (or "opposite") but does not say which direction. Both realisations are equally valid because the constraint is isotropic: it specifies a relationship, not a direction.

5. The Nine Measurement Configurations

Table 1 enumerates all logically distinct configurations for an entangled pair. Every possible measurement scenario falls into one of these nine cases.

Table 1. All nine logically distinct measurement configurations for an entangled pair with the "same" constraint ($\kappa_{ij} = \kappa_0 \delta_{ij}$). $\Delta\theta = \theta_A - \theta_B$. "Environmental" denotes an uncontrolled inscription with $\Delta S > 0$ but no recorded axis. For the "opposite" constraint (ε_{ij}), Cases 4 and 6 swap results.

Case	Alice	Bob	Result	What is physically happening
1	Measures at θ_A	Measures at θ_B	$\cos^2\Delta\theta$	Both keys presented. Full contraction. Layer 2 readable.
2	Measures at θ_A	Does not measure	$\frac{1}{2}$	One key. Partial contraction. Bob sees maximally mixed. No trace of Alice.
3	Does not measure	Measures at θ_B	$\frac{1}{2}$	Mirror of Case 2. Alice's choice irrelevant.
4	$\theta_A = 0^\circ$	$\theta_B = 0^\circ$	1	Aligned axes. Deterministic.
5	$\theta_A = 0^\circ$	$\theta_B = 45^\circ$	$\frac{1}{2}$	Half overlap. Indistinguishable from uncorrelated.
6	$\theta_A = 0^\circ$	$\theta_B = 90^\circ$	0	Orthogonal axes. Deterministic anti-correlation.
7	Environmental	Measures at θ_B	$\frac{1}{2}$	Axis unknown. Layer 2 closed but key lost. Decoherence.
8	Environmental	Environmental	Undecidable	Both keys lost. Layer 2 permanently inaccessible. Classical reality.
9	Neither	Neither	Open	No inscription. Entanglement persists indefinitely.

The Cross-Term Kill

When Alice's particle undergoes environmental inscription (Case 7), summing $|C_2|^2$ over both environmental outcomes and averaging over all possible θ_{env}:

$$P = \int_0^{2\pi} \frac{\mathrm{d}\theta_{\text{env}}}{2\pi} \left[\cos^2\theta_{\text{env}} \cos^2\theta_B + \sin^2\theta_{\text{env}} \sin^2\theta_B \right] = \frac{1}{2}. \tag{17}$$

The cross-terms $2\cos\theta_{\text{env}} \sin\theta_{\text{env}} \cos\theta_B \sin\theta_B$ cancel exactly. This is the *cross-term kill theorem*: one environmental inscription converts the coherent sum $\left|\sum \text{amplitudes}\right|^2$ into the incoherent sum $\sum|\text{amplitude}|^2$. The transition is exact, immediate, and idempotent [17].

Structural no-signalling. Cases 2 and 3 prove that no operation by Alice can alter Bob's Layer 1 statistics, and vice versa. The correlation lives exclusively in Layer 2, which has no three-dimensional spatial address. No-signalling is a geometric consequence of the layer separation.

Retrocausality dissolved. Cases 1 - 3 prove that the temporal ordering of measurements is irrelevant. Layer 2 closure is *and*, not *then*. Whether Alice measures first, second, or simultaneously with Bob, the correlation is $\cos^2(\Delta\theta)$.

6. No-Signalling: Structural and Thermodynamic

6.1. The Structural Proof

Theorem 1 (No-signalling, structural~) *For an entangled pair with inscription tensor* κ_{ij} *of rank 2, no local operation by Alice can alter Bob's measurement statistics. This follows from the contraction rules of the rank-2 tensor* δ_{ij} *and the identity* $\cos^2\alpha+\sin^2\alpha=1$. *The proof is exact, non-circular, and validated against the full experimental record [4]-[6] [17].*

6.2. The Thermodynamic Beacon Argument

Theorem 2 (No-signalling, thermodynamic~) *Signalling requires a physical trace at the receiver. Layer 1 traces are local and subluminal: they cannot constitute signalling at spacelike separation. Layer 2 produces no physical trace at the distant party (Section 2). There is nothing to detect and nothing to propagate. No-signalling holds.*

No-signalling holds structurally (tensor contraction) and physically (thermodynamic propagation limits), from independent premises, converging on the same conclusion [15].

6.3. The Neptune Protocol: Why FTL Communication Fails

To make the no-signalling result concrete, consider the following protocol designed to communicate faster than light [15] [17].

Alice is on Earth. Bob is near Neptune, approximately 4.3 light-hours away. They share a large supply of entangled pairs prepared in the "same" constraint ($\kappa_{ij}=\kappa_0\delta_{ij}$), and they pre-agree on a schedule: at specific times, both will measure their particles at aligned angles ($\Delta\theta=0^\circ$). The encoding is simple. Alice either measures her particles at the agreed time (ON—representing a 1) or does nothing (OFF—representing a 0). By running many pairs at each time slot, Alice encodes a binary message—a distress signal, a greeting, anything.

If signalling worked, Bob could decode the message from his data alone. At $\Delta\theta=0^\circ$ with the "same" constraint, the correlation is deterministic: every pair should agree. If Alice measures and the correlation is real, perhaps Bob's outcomes would show structure. If Alice does not measure, perhaps they would not. Bob decodes Alice's ON/OFF pattern 4.3 light-hours before any classical signal could arrive.

The protocol fails. Bob's data are $P=\frac{1}{2}$ in every time slot—ON and OFF—because partial contraction of the rank-2 tensor with any single detector axis yields $\frac{1}{2}$, forced by $\cos^2\alpha+\sin^2\alpha=1$ (Equation (16)). The total-variation distance between Bob's distributions in ON and OFF slots is [15]:

$$\Lambda = \frac{1}{2}\int \mathrm{d}x \left| P_B^{(\mathrm{ON})}(x) - P_B^{(\mathrm{OFF})}(x) \right| = 0. \tag{18}$$

The correlation is real—but it lives in Layer 2, accessible only through coincidence matching (both keys required). Bob alone has one key. One key reads as maximally mixed. The deterministic correlation at $\Delta\theta = 0^\circ$ is visible only in the joint record, which requires classical communication to construct.

The thermal argument closes the second avenue. When Alice measures her particles, the inscription event produces heat flow, spectral shifts, and entropy increase—all at Earth, at Alice's detector. This is Layer 1: local, thermal, subluminal. No thermal beacon appears at Neptune. No spectral shift on Bob's qubits. No entropy change in Bob's cryostat. Bob's detector registers a sequence of fair coin flips containing exactly zero bits of mutual information with Alice's message [17]. No algorithm, no statistical test, no machine learning model can extract what is not there [15].

7. Entropy-Aware CHSH and the Local Ceiling at $2\sqrt{2}$

7.1. Detectors as Local Contraction Channels

In each run with settings a, b, the measured correlator is reduced by local detector factors $L_A(a), L_B(b) \in (0,1]$ that encode all entropy couplings (thresholds, dissipation channels, bath mismatch). We model

$$E(a,b) = -L_A(a) L_B(b) \cdot \cos 2(a-b). \tag{19}$$

This preserves locality (outcome at A depends only on λ, μ_A, a; at B only on λ, μ_B, b) and measurement independence (settings are chosen independently). It merely rejects the false premise that detectors are thermodynamically inert.

7.2. $L_{A,B}$ versus Standard Detection Efficiency

Standard detection efficiency η_{det} measures the probability that a photon arriving at the detector produces a click—a ratio of detected events to incident events. It governs the detection loophole [23] [24]: if η_{det} is too low, post-selection of detected events can mimic Bell violations.

The contraction factors $L_{A,B}$ encode a different physical quantity. They measure the degree to which the detector's thermodynamic interaction with the photon preserves the correlation structure. Even a detector with unit efficiency ($\eta_{\mathrm{det}} = 1$, every photon produces a click) imposes an entropy-aware contraction: the polariser's projection geometry sorts incoming amplitude into allowed and forbidden channels (Equation (8)), and additional entropy channels (bath mismatch, thermal noise, impedance mismatch) reduce the effective correlator below unity.

$L_{A,B} = 1$ corresponds to an ideal analyser where the only entropy cost is the projection itself. $L_{A,B} < 1$ corresponds to additional entropy channels beyond the projection. Within the broader framework [22], L is governed by the local accessibility field $Z(x,\phi)$: $L \to 1$ as detector accessibility approaches ideal ($Z \to 1$), and L decreases as entropy channels accumulate ($Z \to 0$).

Calibration routine. $L_A L_B$ is extracted from aligned-basis ($\Delta\theta = 0^\circ$) anti-correlation visibility:

$$V_0 = \left|E(a,b)\right|_{\Delta\theta=0} = L_A(a) L_B(b). \tag{20}$$

For a singlet pair, the ideal correlator at $\Delta\theta = 0$ is $E = -1$. The measured value gives $L_A L_B$ directly. For symmetric optical paths, $L_A \approx L_B \approx \sqrt{V_0}$.

7.3. CHSH with Contraction: Full Derivation

Define the CHSH combination

$$S = \left|E(a,b) + E(a,b') + E(a',b) - E(a',b')\right|. \tag{21}$$

Theorem 3 (Entropy-aware CHSH ceiling). *For the entropy-aware correlator (19) with* $L_{A,B} \in (0,1]$ *approximately setting-independent,*

$$S \le 2\sqrt{2} L_A L_B. \tag{22}$$

Proof. Substituting Equation (19) into Equation (21) and applying the triangle inequality:

$$\begin{aligned} S \le\ & L_A(a) L_B(b)\left|\cos 2\Delta\theta_1\right| + L_A(a) L_B(b')\left|\cos 2\Delta\theta_2\right| \\ & + L_A(a') L_B(b)\left|\cos 2\Delta\theta_3\right| + L_A(a') L_B(b')\left|\cos 2\Delta\theta_4\right|. \end{aligned} \tag{23}$$

Since each $L \le 1$:

$$S \le \left|\cos 2\Delta\theta_1\right| + \left|\cos 2\Delta\theta_2\right| + \left|\cos 2\Delta\theta_3\right| + \left|\cos 2\Delta\theta_4\right| \le 4. \tag{24}$$

The algebraic maximum 4 is not physical. The CHSH-optimal polariser angles are:

$$a = 0^\circ,\quad a' = 45^\circ,\quad b = 22.5^\circ,\quad b' = -22.5^\circ. \tag{25}$$

These give four angular separations of 22.5° in polariser angle, which is 45° in the correlation argument $2(a-b)$:

$$2(a-b) = 2\left(0^\circ - 22.5^\circ\right) = -45^\circ \ \Rightarrow\ \cos\left(-45^\circ\right) = 1/\sqrt{2}, \tag{26}$$

$$2(a-b') = 2\left(0^\circ + 22.5^\circ\right) = 45^\circ \ \Rightarrow\ \cos\left(45^\circ\right) = 1/\sqrt{2}, \tag{27}$$

$$2(a'-b) = 2\left(45^\circ - 22.5^\circ\right) = 45^\circ \ \Rightarrow\ \cos\left(45^\circ\right) = 1/\sqrt{2}, \tag{28}$$

$$2(a'-b') = 2\left(45^\circ + 22.5^\circ\right) = 135^\circ \ \Rightarrow\ \cos\left(135^\circ\right) = -1/\sqrt{2}. \tag{29}$$

Evaluating the four correlators:

$$2E(a,b) = -L_A(a) L_B(b)\left(1/\sqrt{2}\right),\quad E(a,b') = -L_A(a) L_B(b')\left(1/\sqrt{2}\right), \tag{30}$$

$$E(a',b) = -L_A(a') L_B(b)\left(1/\sqrt{2}\right),\quad E(a',b') = -L_A(a') L_B(b')\left(-1/\sqrt{2}\right). \tag{31}$$

The CHSH combination becomes:

$$\begin{aligned} S &= \left| E(a,b) + E(a,b') + E(a',b) - E(a',b') \right| \\ &= \frac{1}{\sqrt{2}} \left[L_A(a) L_B(b) + L_A(a) L_B(b') + L_A(a') L_B(b) + L_A(a') L_B(b') \right] \\ &= \frac{1}{\sqrt{2}} \left[L_A(a) \left(L_B(b) + L_B(b') \right) + L_A(a') \left(L_B(b) + L_B(b') \right) \right] \\ &= \frac{1}{\sqrt{2}} \left(L_A(a) + L_A(a') \right) \left(L_B(b) + L_B(b') \right). \end{aligned} \tag{32}$$

Since $L \le 1$:

$$L_A(a) + L_A(a') \le 2, \quad L_B(b) + L_B(b') \le 2. \tag{33}$$

Therefore:

$$S \le \frac{1}{\sqrt{2}} \times 2 \times 2 = \frac{4}{\sqrt{2}} = 2\sqrt{2}. \tag{34}$$

This is Tsirelson's bound [8], recovered from strict locality plus entropy-aware detectors. For setting-independent contraction ($L_A(a) \approx L_A(a') \approx L_A$ and $L_B(b) \approx L_B(b') \approx L_B$):

$$S \le \frac{1}{\sqrt{2}} (2L_A)(2L_B) = 2\sqrt{2} L_A L_B. \tag{35}$$

□

Interpretation. The algebraic maximum 4 is the sum of four ideal unit correlators; each analyser + detector interface at the CHSH geometry imposes a projection/diffraction tax of $1 - 1/\sqrt{2}$, leaving $4 \times \left(1/\sqrt{2}\right) = 2\sqrt{2}$. Extra entropy channels ($L < 1$) reduce S further. Experiments never exceed a local, detector-aware ceiling; they saturate it in the best photon platforms.

The critical point: the $2\sqrt{2}$ is not a consequence of detector imperfection. A perfect detector with zero thermal noise, zero bath mismatch, and unit efficiency ($L_A = L_B = 1$) still gives $S \le 2\sqrt{2}$. The ceiling comes from the polariser's projection geometry—the entropy sorting that is intrinsic to measurement itself. At the CHSH-optimal angles, $\cos^2(45^\circ) = \frac{1}{2}$. This is not a loss. It is the physical cost of asking a question at 45˚ to the axis where the answer was written. The polariser sorts; the sorting has a geometry; the geometry sets the ceiling. Bell's bound of 2 is what you get when you pretend the detector contributes nothing. $2\sqrt{2}$ is what you get when you include what the detector physically does.

7.4. Why Bell's "2" Bound Is a False Baseline

Bell bounded $S \le 2$ by assuming outcomes are functions $A(a,\lambda), B(b,\lambda) \in \{\pm 1\}$ with no detector degrees of freedom and perfect sampling. But thresholded, lossy detectors are known to change bounds (detection loophole [23], efficiency thresholds [24]). Our claim is stronger: even with unit efficiency and measurement independence, physical analysers impose an intrinsic, geometry-tied contraction. Once the detector is modelled as a thermodynamic channel, the relevant local ceiling is (22), not 2.

The layer distinction sharpens this point. Bell's locality condition assumes that the correlational structure and the measurement apparatus inhabit the same physical space—three-dimensional space. They do not. Layer 1 is local in three-dimensional space. Layer 2 lives in configuration space, where spatial separation is not defined. Bell proved that correlations cannot be explained by structure in three dimensions. He was right. The structure lives elsewhere [16].

7.5. Graph-Theoretic Normalisation

In the exclusivity-graph framing [25], the quantum-over-classical advantage for the 8-event CHSH graph is $\vartheta/\alpha = 2\left(2-\sqrt{2}\right) \approx 1.172$. This is the universal deficit from the algebraic 4 to the physical ceiling $2\sqrt{2}$: $4-2\sqrt{2} = 2\left(2-\sqrt{2}\right)$. It is not a surplus demanding nonlocality; it is the detector tax demanded by entropy-aware projection at 45˚.

8. The Measurement Problem Dissolved

8.1. The Conflation

Standard quantum mechanics uses the word "collapse" to describe a single event: the transition from superposition to definite outcome upon measurement. Decoherence theory [13] refines this into a continuous process. Neither treatment distinguishes between what happens to the measured particle (Layer 1) and what happens to the correlation with a distant particle (Layer 2). The present framework makes this distinction precise and shows that the measurement problem is a category error produced by conflating two physically distinct events into a single word.

8.2. Two Physically Different Events

Layer 1 inscription (Section 2): the detector physically interacts with the particle. Heat flows. Spectral shifts occur. The photon is absorbed. The outcome is permanently selected. Local, thermal, irreversible.

Layer 2 key burial: the local inscription adds one key to the Layer 2 entry in configuration space. No thermal consequence at the distant party—confirmed across every platform (Section 2). The correlation is buried, not destroyed. Recovery through post-selection is perfect [10]-[12] [26] [27]—the experimental proof that Layer 2 was never destroyed.

These are not two aspects of one event. They are two different physical processes with different thermodynamic signatures, different spatial addresses, and different recoverability.

8.3. Superposition Until Interaction, Not Observation

Superposition ends when a particle physically interacts with something that performs an irreversible act ($\Delta S > 0$). A detector. A polariser. A dust grain. This is interaction, not observation. The particle does not respond to consciousness, human attention, or laboratory notebooks. It responds to thermodynamic events.

A macroscopic object undergoes inscription events continuously—approximately 10^{23} environmental interactions per second. A macroscopic object is never in superposition because it is being inscribed by its environment at a rate beyond practical count. The Geiger counter in Schrödinger's thought experiment is an inscription device. It fires the moment it detects the decay particle. $\Delta S > 0$. The cat is alive or dead. The box is irrelevant.

8.4. Decoherence Theory Is Half Right

Standard decoherence theory [13] correctly identifies the suppression of local interference: after environmental interaction, the singles data carry no trace of the correlation. This is the Layer 1 effect, and it is real. What decoherence theory gets wrong is the interpretation: it frames the suppression as information degradation—a gradual, irreversible loss of quantum coherence. The cross-term kill theorem (Equation (17)) shows that the transition is exact at the first completed inscription event (not gradual), and the information is structurally intact (not lost). What grows with subsequent inscriptions is not the degree of suppression but the number of keys required for recovery.

9. Bell's Theorem: What the Violation Detects

Bell's theorem [1] proves that no local hidden variable model can reproduce the quantum predictions for entangled pairs. The CHSH inequality [2] bounds $S \le 2$ for any model in which outcomes are predetermined by a shared variable λ and each party's result depends only on their local setting and λ. Quantum mechanics reaches $|S| = 2\sqrt{2}$, confirmed experimentally [3]-[6] [9].

Bell's hidden variables λ are implicitly three-dimensional objects: they carry predetermined outcomes as functions of detector angles, and the locality condition requires that these outcomes depend only on λ and the local setting. We read this as the assumption that the correlational structure and the measurement apparatus inhabit the same physical space—three-dimensional space—so that the locality constraint applies to both.

The violation to $2\sqrt{2}$ is the signature of the correlation structure living in configuration space—a space the detectors access through the polariser angle but do not inhabit. Bell proved that correlations cannot be explained by structure in three dimensions. He was right. The structure lives elsewhere.

10. Einstein Vindicated

Einstein objected to quantum mechanics on the grounds that it appeared to require "spooky action at a distance" [28].

There is no action. Layer 1 is strictly local. The photodiode absorbs the photon at its location. Nothing happens at the distant particle [15].

There is no distance. Layer 2 is a geometric object in configuration space with no three-dimensional address. The correlation was written at the crystal, at the moment of pair creation, into a space where spatial separation does not apply.

Einstein was right that action at a distance is unphysical. He was wrong about the alternative: he proposed local hidden variables in three-dimensional space. Bell ruled that out. The resolution is that the correlation lives in a space where "local" and "distant" are not defined concepts, and the measurement events that access it are strictly local in the space where locality applies.

11. Photon-Only Methods and Predictions

11.1. Platforms and Temperatures

We restrict to photonic Bell tests with SNSPDs operated at $T \sim 0.6\text{-}2\ \text{K}$ and low-jitter readout. Optics are kept inside the cryostat when possible; otherwise, fibres and windows are audited for blackbody glow and fluorescence. Time-bin encoding (unbalanced interferometers) can remove polarisers as entropy sinks; polarisation tests provide the baseline.

11.2. Settings Protocol

To avoid hidden sequential correlations, run: 1) Start at a non-aligned angle. 2) Perform a randomised walk over analyser angles drawn from a QRNG. 3) Return to the original aligned angle and re-check anti-correlation. Any drift indicates entropy-memory or setting-dependent leakage (L varying with time/basis).

11.3. Primary Observables

$S(T)$: CHSH vs detector-stage temperature (monotone increase as $T\downarrow$). $S(\text{encoding})$: polarisation vs time-bin; removing polarisers should increase L. Full event logs: include non-clicks and dark counts; no post-selection.

11.4. Model Fit and Falsifiers

Fit L_A, L_B from aligned-basis anti-correlation and from visibility via Equation (9). Then predict S via Equation (22) without free angular parameters. Falsifiers: 1) Observed S exceeding $2\sqrt{2}$ at fixed $L_{A,B}$ and geometry (contradicts (22)). 2) No $S(T)$ monotonicity with controlled changes in entropy budget. 3) Time-bin encoding fails to raise S relative to polarisation with identical losses.

12. Falsifiable Predictions

Beyond the experimental proposals above, the layer separation generates four additional falsifiable predictions:

F4. Layer 1/Layer 2 separability. Layer 2 correlations produce zero thermal or spectral signature at the distant party. A reproducible nonlocal thermal signature would falsify the layer separation [15].

F5. Perfect recovery. Post-selection recovery is always perfect, regardless of delay, distance, or intermediate interactions. Imperfect recovery scaling with any parameter indicates information degradation, falsifying key burial [15].

F6. Cross-term kill sharpness. The quantum-to-classical transition is exact at the first environmental inscription, not gradual. Tuneable coupling should show a sharp CHSH transition from $S = 2\sqrt{2}$ to $S \le 2$ at one inscription event [18].

F7. No observer dependence. The outcome depends on whether a physical interaction occurred ($\Delta S > 0$), not on whether the result was observed by a conscious agent.

13. Conclusions

We have replaced Bell's detectorless abstraction with a physically explicit, entropy-aware measurement model. Between source and coincidence, at least five distinct events occur: the crystal inscribes the constraint, the polariser reads it non-destructively, the photodiode absorbs the photon ($\Delta S \gg 0$, Layer 1 collapse), the coincidence circuit opens the pair layer, and Alice's and Bob's measurements proceed independently at spacelike separation. Bell's theorem collapses all five into a single function. The layer separation distinguishes them: Layer 1 (local, thermal, irreversible) and Layer 2 (non-thermal, inscribed at the source, persisting in configuration space).

The allowed/forbidden entropy accounting yields a strictly local CHSH ceiling of $2\sqrt{2}L_A L_B$. Quantum photonic tests approach this ceiling because photons are minimal carriers and SNSPDs can be made nearly entropy-neutral; heavier carriers naturally sit below due to larger entropy channels. In this view, nothing "nonlocal" is required: the celebrated 2.828 is the residual after four projection/diffraction taxes at 45˚.

The measurement problem is dissolved. "Collapse" is a conflation of two physically distinct events: Layer 1 thermodynamic inscription (local, thermal, irreversible) and Layer 2 key burial (non-thermal, non-propagating, perfectly recoverable). Neither is mysterious. Neither requires a special postulate. Neither depends on an observer.

Bell's violation detects that the correlation structure lives in configuration space, not in three-dimensional space. Einstein's objection to action at a distance is vindicated: there is no action (Layer 1 is local) and there is no distance (Layer 2 has no three-dimensional address).

Standard quantum mechanics had the mathematics. It lacked the ontological commitment to read what the mathematics was saying.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Bell, J.S. (1964) On the Einstein Podolsky Rosen Paradox. *Physics Physique Fizika*, **1**, 195-200. https://doi.org/10.1103/physicsphysiquefizika.1.195

[2] Clauser, J.F., Horne, M.A., Shimony, A. and Holt, R.A. (1969) Proposed Experiment to Test Local Hidden-Variable Theories. *Physical Review Letters*, **23**, 880-884. https://doi.org/10.1103/physrevlett.23.880

[3] Aspect, A., Dalibard, J. and Roger, G. (1982) Experimental Test of Bell's Inequalities Using Time-Varying Analyzers. *Physical Review Letters*, **49**, 1804-1807. https://doi.org/10.1103/physrevlett.49.1804

[4] Hensen, B., Bernien, H., Dréau, A.E., Reiserer, A., Kalb, N., Blok, M.S., *et al.* (2015) Loophole-Free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres. *Nature*, **526**, 682-686. https://doi.org/10.1038/nature15759

[5] Shalm, L.K., Meyer-Scott, E., Christensen, B.G., Bierhorst, P., Wayne, M.A., Stevens, M.J., *et al.* (2015) Strong Loophole-Free Test of Local Realism. *Physical Review Letters*, **115**, Article ID: 250402. https://doi.org/10.1103/physrevlett.115.250402

[6] Giustina, M., Versteegh, M.A.M., Wengerowsky, S., Handsteiner, J., Hochrainer, A., Phelan, K., *et al.* (2015) Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons. *Physical Review Letters*, **115**, Article ID: 250401. https://doi.org/10.1103/physrevlett.115.250401

[7] Handsteiner, J., Friedman, A.S., Rauch, D., Gallicchio, J., Liu, B., Hosp, H., *et al.* (2017) Cosmic Bell Test: Measurement Settings from Milky Way Stars. *Physical Review Letters*, **118**, Article ID: 060401. https://doi.org/10.1103/physrevlett.118.060401

[8] Cirel'son, B.S. (1980) Quantum Generalizations of Bell's Inequality. *Letters in Mathematical Physics*, **4**, 93-100. https://doi.org/10.1007/bf00417500

[9] Storz, S., Schär, J., Kulikov, A., Magnard, P., Kurpiers, P., Lütolf, J., *et al.* (2023) Loophole-Free Bell Inequality Violation with Superconducting Circuits. *Nature*, **617**, 265-270. https://doi.org/10.1038/s41586-023-05885-0

[10] Kim, Y., Yu, R., Kulik, S.P., Shih, Y. and Scully, M.O. (2000) Delayed "Choice" Quantum Eraser. *Physical Review Letters*, **84**, 1-5. https://doi.org/10.1103/physrevlett.84.1

[11] Walborn, S.P., Terra Cunha, M.O., Pádua, S. and Monken, C.H. (2002) Double-Slit Quantum Eraser. *Physical Review A*, **65**, Article ID: 033818. https://doi.org/10.1103/physreva.65.033818

[12] Ma, X., Kofler, J., Qarry, A., Tetik, N., Scheidl, T., Ursin, R., *et al.* (2013) Quantum Erasure with Causally Disconnected Choice. *Proceedings of the National Academy of Sciences of the United States of America*, **110**, 1221-1226. https://doi.org/10.1073/pnas.1213201110

[13] Zurek, W.H. (2003) Decoherence, Einselection, and the Quantum Origins of the Classical. *Reviews of Modern Physics*, **75**, 715-775. https://doi.org/10.1103/revmodphys.75.715

[14] Palacios-Laloy, A., Mallet, F., Nguyen, F., Ong, F., Bertet, P., Vion, D., *et al.* (2009) Spectral Measurement of the Thermal Excitation of a Superconducting Qubit. *Physica Scripta*, **137**, Article ID: 014015. https://doi.org/10.1088/0031-8949/2009/t137/014015

[15] Atoyo, J.K. and Ogiamien, I. (2026) The Thermodynamic Closure of No-Signaling: Layer Separation, Key Burial, and the Non-Thermal Character of Entanglement Correlations. Prometheus Engineering Research Group.

https://doi.org/10.5281/zenodo.20578417

[16] Atoyo, J.K. and Ogiamien, I. (2026) The Dimensional Key: How Entangled Correlations Are Written, Read, and Why the Detector Angle Is a Probe of Configuration Space. Prometheus Engineering Research Group. https://doi.org/10.5281/zenodo.20590672

[17] Atoyo, J.K. and Ogiamien, I. (2026) A Structural Proof of the No-Signaling Theorem. Prometheus Engineering Research Group. https://zenodo.org/records/20569102

[18] Atoyo, J.K. and Ogiamien, I. (2026) Ledger Geometry, Irreducibility, and the Inscription Boundary: Entanglement as Co-Location in the Fourth Spatial Degree, the Arithmetic of Quantum Coherence, and the Mechanism of Proper Time within the Entropic Lattice Ontology. Prometheus Engineering. Research Group. https://zenodo.org/records/20638175

[19] Yamamoto, T. and Tokura, Y. (2024) Heat Flow from a Measurement Apparatus Monitoring a Dissipative Qubit. *Physical Review Research*, **6**, Article ID: 013300. https://doi.org/10.1103/physrevresearch.6.013300

[20] Landauer, R. (1961) Irreversibility and Heat Generation in the Computing Process. *IBM Journal of Research and Development*, **5**, 183-191. https://doi.org/10.1147/rd.53.0183

[21] Bérut, A., Arakelyan, A., Petrosyan, A., Ciliberto, S., Dillenschneider, R. and Lutz, E. (2012) Experimental Verification of Landauer's Principle Linking Information and Thermodynamics. *Nature*, **483**, 187-189. https://doi.org/10.1038/nature10872

[22] Atoyo, J.K. and Ogiamien, I. (2026) Inscription, Accessibility, and the Emergence of Physical Law: The Entropic Lattice Ontology in Engagement with Modern Physics, Prometheus Engineering Research Group. https://doi.org/10.5281/zenodo.20352569

[23] Pearle, P.M. (1970) Hidden-Variable Example Based Upon Data Rejection. *Physical Review D*, **2**, 1418-1425. https://doi.org/10.1103/physrevd.2.1418

[24] Eberhard, P.H. (1993) Background Level and Counter Efficiencies Required for a Loophole-Free Einstein-Podolsky-Rosen Experiment. *Physical Review A*, **47**, R747-R750. https://doi.org/10.1103/physreva.47.r747

[25] Cabello, A., Severini, S. and Winter, A. (2014) Graph-Theoretic Approach to Quantum Correlations. *Physical Review Letters*, **112**, Article ID: 040401. https://doi.org/10.1103/physrevlett.112.040401

[26] Hasegawa, Y., Loidl, R., Badurek, G., Baron, M., Manini, N., Pistolesi, F., *et al.* (2002) Observation of Off-Diagonal Geometric Phases in Polarized-Neutron-Interferometer Experiments. *Physical Review A*, **65**, Article ID: 052111. https://doi.org/10.1103/physreva.65.052111

[27] Lourenço-Martins, H., *et al.* (2024) Quantum Eraser Experiments for the Demonstration of Entanglement between Swift Electrons and Light. arXiv: 2404.11368.

[28] Einstein, A., Podolsky, B. and Rosen, N. (1935) Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? *Physical Review*, **47**, 777-780. https://doi.org/10.1103/physrev.47.777